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THE ELECTRICAL AND METALLURGICAL PROPERTIES OF DEFECTS  
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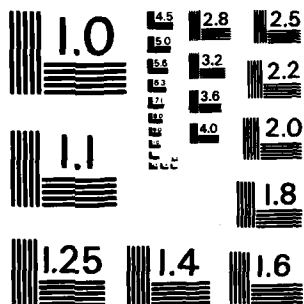
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THE ELECTRICAL AND METALLURGICAL PROPERTIES  
OF DEFECTS IN COMPOUND SEMICONDUCTORS

FINAL REPORT

Covering the period 8 February 1975 through 30 September 1982

Prepared under

Army Research Office, Research Triangle Park  
Contracts DAAG 29-75-0013  
and DAAG 29-78-0018

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DECEMBER 1982

Solid State Electronics Laboratory  
Stanford Electronics Laboratories  
Stanford University      Stanford, California

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes the research carried out under Contracts DAAG 29-75-0013 and DAAG 29-78-0018. The program on the contract was directed toward the following three separate projects related to the electrical, optical, and metallurgical properties of defects in compound semiconductors: 1. Defects in Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals 2. Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ 3. Properties of Heavily Doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$		

# FOREWORD

The studies presented began 8 February 1975 and concluded 30 September 1982. The research activity was conducted under the supervision of Professor Gerald L. Pearson at the Solid State Electronics Laboratory at Stanford University who was also the Principal Investigator.

This is the Final Technical Documentary Report of the work under contracts DAAG 29-75-0013 and DAAG 29-78-0018.

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

THE ELECTRICAL AND METALLURGICAL PROPERTIES OF  
DEFECTS IN COMPOUND SEMICONDUCTORS

ABSTRACT

This report summarizes the research carried out under Contracts DAAG 29-C-0013 and DAAG 29-C-0018. The program on the contract was directed toward the following three separate projects related to the electrical, optical, and metallurgical properties of defects in compound semiconductors:

1. Defects in annealed  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  Single Crystals.
2. Electronic Transport Properties of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .
3. Properties of Heavily Doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .

## CHAPTER I

### INTRODUCTION

This report summarizes the technical activity at Stanford University under contracts DAAG 29-75-0013 and DAAG 29-78-C-0018 during the period 8 February 1975 to 30 September 1982. The program on this contract was directed toward the following three separate projects related to the electrical, optical, and metallurgical properties of defects in compound semiconductors:

1. Defects in Annealed  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  Single Crystals
2. Electronic Transport Properties of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .
3. Properties of Heavily Doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .

A detailed technical report was prepared for each of the first two projects so that only the abstracts are included in this summary report together with a complete bibliography of all technical papers generated by these projects.

The third project on "Properties of Heavily Doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ " was only partially completed prior to the termination of the contract. It will be continued with alternate financing.



## CHAPTER II

### Defects in Annealed $\text{Al}_x\text{Ga}_{1-x}\text{As}$ Single Crystals

#### ABSTRACT

An investigation of the annealing effects in the ternary compound semiconducting system,  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , has been carried out. Nondegenerate n-type single crystals always have p-type surface layers after annealing at  $800^\circ\text{C}$  for 21 hours in a vacuum. The thickness of this converted p-type surface layer is  $\approx 5 \mu\text{m}$  as measured by electron-beam induced current techniques on annealed boat-grown (n)GaAs crystals having an electron concentration of  $\approx 3 \times 10^{16} \text{ cm}^{-3}$ . Capacitance-voltage measurements on the anneal-induced p-n junction shows that it is linearly graded.

Photoluminescent measurements were employed to study the radiative defects in the converted surface layers. Photoluminescent bands due to shallow acceptors such as  $\text{Si}_{\text{As}}$  and  $\text{Si}_{\text{As}}-\text{V}_{\text{As}}$  were detected in annealed  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  single crystals. An oxygen level at 0.71 eV was also detected in annealed GaAs but not in as-grown samples. Besides the bands due to shallow acceptors, broad deep level emission bands were also observed in annealed  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .  $\text{Sn}_{\text{As}}$  deep acceptors were detected in annealed  $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Sn}$  and  $\text{V}_{\text{Ga}}-\text{Te}$  (or  $\text{V}_{\text{Al}}-\text{Te}$ ) complexes in annealed  $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Te}$ . Two prominent bands located at 1.53 and 1.46 eV, independent of Al composition  $x$ , were detected in as-grown (p) $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Ge}$ . The 1.53 eV band is thought to arise from  $\text{V}_{\text{Ga}}-\text{Ge}_{\text{As}}$  complexes. The other has not been identified.  $\text{V}_{\text{As}}-\text{Ge}_{\text{As}}$  complexes were also introduced into  $\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Ge}$  during heat treatment.

Transient capacitance techniques were used to study nonradiative defects in as-grown and annealed samples. Two electron traps were found in as-grown  $(n)\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Sn}$  single crystals when  $x$  was greater than 0.2. One is located 0.08 eV below the conduction band and the ionization energy of the other varies from 0.15 to 0.19 eV as  $x$  increases from 0.21 to 0.35. It is noted that these electron traps are present in the same range of Al composition where the electron activation energy in  $(n)\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Sn}$ , as obtained from Hall measurements, increases sharply with respect to  $x$ . It is believed that this increase in the electron activation energy with respect to  $x$  is caused by the presence of these two electron traps.

A hole trap, introduced by annealing, was found in  $(p)\text{Al}_x\text{Ga}_{1-x}\text{As}:\text{Ge}$ . This level is located 0.42 eV above the top of the valence band and is independent of  $x$ . Arguments are given to show that this trap is due to Ga (or Al) vacancies rather than Cu impurities as reported in the literature. A model is presented to support the view that Ga vacancies are hole traps and As vacancies electron traps.

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The above abstract is from the Ph.D. thesis of Kou-I Chang as given in Report SU-SEL-78-019, Stanford Electronics Laboratories, Stanford, California, June 1978. One technical paper [1] and one oral presentation [2] originated from this work. Dr. Chang is now employed at Hewlett Packard Company, Palo Alto, California.

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## CHAPTER III

### Electronic Transport Properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}$

#### ABSTRACT

The electronic transport properties of holes in p-type  $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$  are systematically investigated. Detailed studies are made of the carrier concentrations, carrier mobilities, impurity activation energy and impurity distribution coefficients.

Single crystal layers of  $\text{Al}_x\text{Ga}_{1-x}\text{As:Ge}$  have been grown throughout the composition range  $0.0 < x < 1.0$  on (100) semi-insulating  $\text{GaAs:Cr}$  substrates using liquid phase epitaxial techniques. The Al distribution coefficient and growth rate at  $800^\circ\text{C}$  are investigated. Carrier concentrations, Hall mobilities and resistivities are measured as a function of temperature from 77 to 300K.

A transport model based upon the relaxation time approach is used to calculate the hole mobility in the degenerate heavy and light hole valence bands of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ . All of the major scattering mechanisms are included in the calculations.

The temperature variation of the hole mobilities are analyzed using theoretical models to determine the relative contributions of each of the scattering processes to the total mobility. Excellent agreement between calculated and experimental mobilities is obtained by considering acoustic deformation potential, piezoelectric, nonpolar optical, polar optical and ionized impurity scattering. The scattering potentials for acoustic deformation potential and nonpolar optical scattering

are determined as  $E_{DP} = 5.25$  eV and  $E_{NP} = 10.65$  eV in GaAs and as  $E_{DP} = 6.84$  eV and  $E_{NP} = 13.65$  eV in AlAs. The major scattering processes which limit the mobility of holes in pure  $Al_xGa_{1-x}As$  are the deformation potential, nonpolar optical and polar optical interactions. The piezoelectric and alloy scattering interactions have a minor effect on the mobility. The lattice mobility of holes in pure  $Al_xGa_{1-x}As$  follows a  $T^{-2.3}$  temperature dependence at all Al compositions. The lattice mobility decreases from  $400$   $cm^2/V\text{-sec}$  in GaAs to  $120$   $cm^2/V\text{-sec}$  in AlAs.

The incorporation of Ge as an amphoteric impurity in  $Al_xGa_{1-x}As$  is investigated. The Ge activation energy increases with Al composition as  $E_A(x) = 10 + 175x$  meV. The total acceptor concentrations, donor concentrations and degree of compensation in the  $Al_xGa_{1-x}As:Ge$  crystals are determined. The distribution coefficient of Ge at both acceptor sites and donor sites decreases exponentially with increasing Al composition. The  $Al_xGa_{1-x}As:Ge$  crystals become closely compensated with increasing Al composition. The acceptor to donor concentration ratio is  $N_A/N_D = 2.7$  in GaAs and decreases to  $N_A/N_D \sim 1$  in AlAs.

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The above abstract is from the Ph.D. thesis of Kevin Gene Wah Jew, Stanford Electronics Laboratories, Stanford, California, March 1982. One technical paper [3] originated from this work and a second [4] is in preparation. Dr. Jew is now employed at Philips Research Laboratories, Sunnyvale, California.

## CHAPTER IV

### Properties of Heavily Doped AlGaAs

#### ABSTRACT

Work this year has involved further characterization of heavily doped AlGaAs. Of particular interest has been determination of the mechanisms involved in the photoluminescence spectra observed in both degenerate n type AlGaAs:Te and degenerate p-type AlGaAs:Ge. In AlGaAs:Te with low Al compositions, above band gap luminescence is observed. This has been attributed to a Burstein-Moss type shift involving very little distortion of the conduction band. Attempts are under way to correlate the peak position with electron density and the peak shape with the joint density of states. Also observed in AlGaAs:Te is a previously unreported infrared peak at 0.95 eV. This peak, which occurs for all levels of Te doping, may be due to a Ga-Te complex.

In AlGaAs:Ge, significant distortion of the valence band is believed to occur. The large hole effective mass prevents screening of the acceptor impurity levels and thus permits the formation of band edge tails and impurity bands. Therefore the peak luminescence energy occurs at an energy lower than the intrinsic band gap. Models are being developed to explain both the peak position and peak width as a function of hole concentration for various Al compositions.

Finally an anomalous peak is observed in structures consisting of heavily doped epitaxial layers grown on GaAs:Cr substrates. While other investigators have attributed a luminescence peak at 1.43 eV to

the substrate, our studies show that if this peak originates from the substrate, it is induced by the epitaxial layer. Samples with epitaxial layers thinner than 0.5  $\mu\text{m}$  show no evidence of this peak, while in samples with thicker epitaxial layer, this peak can predominate. Its asymmetric shape and the properties already mentioned make this characterization a prime goal of future work.

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The above abstract describes the research project of Kevin Malloy. He expects to complete this work and meet all requirements for the Ph.D. degree in August 1983. Mr. Malloy is in the ROTC program and will report for active duty at the Wright-Patterson Air Force Base after receiving his degree.

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4. "Electronic Transport Properties of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ", K. G. W. Jew and G. L. Pearson, Paper in preparation.

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